

Relativistic Gravity and Binary Radio Pulsars

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Abstract.

Following a summary of the basic principles of pulsar timing, we present a review of recent results from timing observations of relativistic binary pulsars. In particular, we summarize the status of timing observations of the much celebrated original binary pulsar PSR B1913+16, draw attention to the recent confirmation of strong evidence for geodetic precession in this system, review the recent measurement of multiple post-Keplerian binary parameters for PSR B1534+12, and describe the Parkes Multibeam survey, a major survey of the Galactic Plane which promises to discover new relativistic binary pulsar systems.

INTRODUCTION

Not long after Einstein proposed his General Theory of Relativity, a variety of experimental tests to be done with solar system objects was suggested. These included the measurement of the perihelion advances of planets, the bending of light rays by the Sun, and radar echo delays from planets. However, such tests were limited by the fact that the effects to be measured were tiny perturbations on a classical description. They only verified the theory in the “weak-field” limit, akin to studying a function by only considering its Taylor expansion about zero. The “strong-field” regime, in which GR effects are more than a perturbation and a classical description is grossly violated, probably at first appeared inaccessible to Earth-bound observers.

The discovery of the first binary pulsar, PSR B1913+16, by Hulse & Taylor (1975) radically changed this situation. This binary system, consisting of two neutron stars in an eccentric 8 hr binary orbit, has permitted precise tests of GR predictions for the first time in the strong-field regime [Taylor & Weisberg 1982, Taylor & Weisberg 1989]. Thus far, GR has passed all tests with flying colours.

In this review, after an introduction to pulsars and pulsar timing, we present the most recent results of observations of PSR B1913+16, as well as of PSR B1534+12,

the second discovered binary pulsar system suitable for sensitive GR studies. We also describe a search for new pulsars that is currently underway, and which promises to find more such objects. For previous excellent reviews of relativistic binary pulsars and their experimental constraints on strong-field relativistic gravity see Taylor et al. (1992) and Damour & Taylor (1992).

RADIO PULSARS: SOME BACKGROUND

Pulsars are rotating, magnetized neutron stars. They exhibit beams of radio emission that can be observed, by a fortuitously located astronomer, as pulsations, once per rotation period. In the published literature there are 708 pulsars known (but see section “Parkes Multibeam Survey” below), all but a handful of which are in the Milky Way, the remainder being in the Magellanic Clouds. Known pulse periods range from a few seconds down to 1.5 ms. These pulse periods are observed to increase steadily, indicative of spin-down due to magnetic dipole radiation. From the observed pulse period and rate of spin-down of a pulsar, the magnitude of the dipole component of the stellar magnetic field, as well as an age estimate, can be deduced. See Lyne & Smith (1998) for a complete review of the properties of radio pulsars.

For our purposes here, we need highlight only two properties of radio pulsars: the stabilities of the radio pulse profile and the stellar rotation. By “pulse profile” we mean the result of the addition of many (typically thousands) of individual pulses, by folding the sampled radio telescope power output modulo the apparent pulse period. Two examples of such pulse profiles are shown in Figure 1. Average profiles are observed to be stable in that the summation of any few thousand consecutive pulses always results in the same pulse profile for a given radio pulsar at a given observing frequency, even though individual pulse morphologies vary greatly. Currently there is no theory to explain this observation; in radio pulsar timing it is simply accepted as fact. Less surprising perhaps is the observed rotational stability. In a reference frame not accelerating with respect to the pulsar, the observed times of pulsations (or TOAs, for times-of-arrival) are generally predictable with high precision, given only the pulse period and spin-down rate. This, we argue, is less surprising than the profile stability because of the large stellar moment of inertia and absence of external torques, in strong contrast to accreting neutron stars whose rotation is much less stable [e.g. Bildsten et al. 1997].

PULSAR TIMING

The combination of pulse profile and rotational stability makes a radio pulsar useful as an extremely precise clock; in some cases the stability of the pulsar-clock is comparable to those of the world’s best atomic time standards [e.g. Kaspi, Taylor & Ryba 1994]. However, the realization of this stability can come only after effects extrinsic to the pulsar are accounted for. In particular, TOAs measured

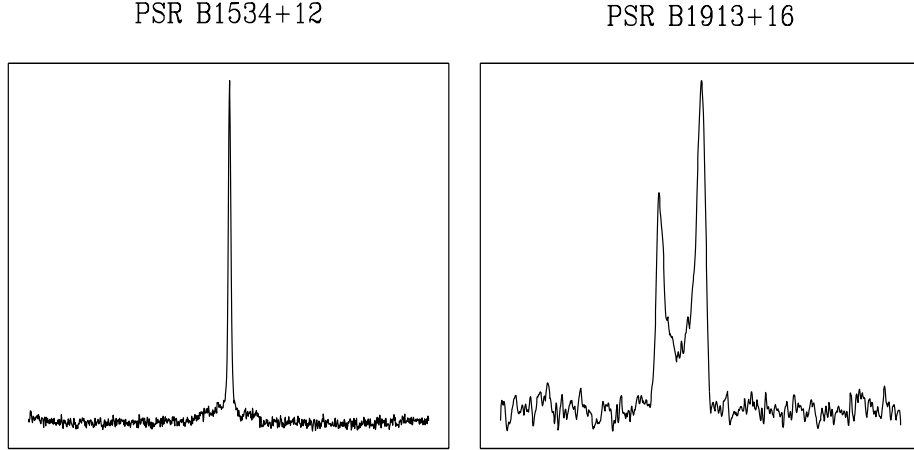


FIGURE 1. Average pulse profiles for PSR B1534+12 [after Kramer et al. 1998], and PSR B1913+16 (courtesy M. Kramer), both at radio frequencies near 1400 MHz.

at an Earth-bound radio telescope must be transformed to a reference frame that is not accelerating with respect to the pulsar. For this purpose, the solar system barycentre reference frame is generally used.

Standard pulsar timing thus consists of observing a pulsar at a radio telescope continuously over many cycles. The start time of the observations is recorded with high precision, and the sampled telescope power output is folded at the topocentric (i.e. apparent) pulse period. The resulting average pulse profile is cross-correlated with a high signal-to-noise template (e.g. Fig. 1) in order to determine the arrival time of the average pulse. That time is then transformed to the solar system barycentre. This transformation can be summarized by the expression

$$t_{\text{SSB}} = t_{\text{O}} + \Delta t_{\text{C}} + \Delta t_{\text{R}} + \Delta t_{\text{E}} + \Delta t_{\text{S}} + \Delta t_{\text{D}}, \quad (1)$$

where t_{SSB} is the pulse arrival time at the solar system barycentre (typically in Barycentric Dynamical Time), t_{O} is the arrival time as observed at an Earth-bound radio telescope, Δt_{C} is the difference between the observatory clock and a suitably stable atomic time standard (such as Terrestrial Dynamical Time), Δt_{R} is the Roemer delay, or the difference in arrival time of a pulse at the solar system barycentre and at the observatory due to the geometric path length difference, Δt_{E} is the Einstein delay due to (weak-field) GR effects in the solar system, and Δt_{S} is the so-called “Shapiro delay,” which depends logarithmically on the impact parameter of the Earth-pulsar and Earth-Sun line of sights. Note that Δt_{R} , Δt_{E} and Δt_{S} require precise knowledge of the sky coordinates of the pulsar; this is turned around so that if observations of the source are available over at least one year, the known motion of the Earth in its orbit permits the measurement of the pulsar’s coordinates with high precision. The last term, Δt_{D} , is an observing frequency-dependent term that accounts for the dispersion of radio waves in the ionized interstellar medium according to the cold plasma dispersion law. The delay term is

proportional to DM/f^2 , where DM is the dispersion measure, or integrated electron density along the line of sight, and f is the observing frequency. The measured DM , together with a model for the distribution of free electrons in the Galaxy [e.g. Taylor & Cordes 1993], provides an estimate of the distance to a pulsar. Details of all the above terms can be found in various references [e.g. Manchester & Taylor 1977].

The above procedure for timing a pulsar of interest is repeated typically on a bi-weekly or monthly basis, so that the spin and astrometric parameters are improved in an iterative fashion: the squares of the residual differences between the initial model-predicted TOAs and the observed TOAs are minimized by varying, and hence improving, the model parameters. The transformation and subsequent determination of the five optimal spin and astrometric parameters (the period P , its rate of change \dot{P} , two sky coordinates and DM) are done using a publically available software package, `tempo`, which consists of several thousand lines of Fortran code¹. Note that by using TOAs, as opposed to measuring the pulse period at each observing epoch, the timing analysis is coherent in the sense that every rotation of the neutron star is accounted for.

TIMING BINARY PULSARS

If the pulsar is in a binary system, its motion about the binary centre of mass will cause regular delays and advances in observed TOAs just as the Earth's motion around the Sun does.² Classically, five additional parameters are required to describe and predict pulse arrival times for binary pulsars, in addition to the five spin and astrometric parameters. Conventionally the five Keplerian parameters are the orbital period P_b , the projected semi-major axis $a \sin i$, where i is the inclination angle of the orbit, the orbital eccentricity e , the longitude of periastron ω measured from the line defined by the intersection of the plane of the orbit and the plane of the sky, and an epoch of periastron T_0 . Only the projected semi-major axis is measurable, as pulsar timing is only sensitive to the radial component of the pulsar's motion. Therefore, the component masses cannot be uniquely determined. Note that under certain circumstances, even in a classical system, the five Keplerian parameters may be insufficient to fully describe the orbit; for example, in the binary pulsar PSR J0045–7319, classical spin-orbit coupling induces post-Keplerian dynamical effects, a result of the quadrupole moment of the pulsar's rapidly rotating B-star companion [Lai, Bildsten, & Kaspi 1995, Kaspi et al. 1996].

In some binary systems, particularly double neutron star binaries, relativistic effects must also be taken into account in order to model the binary orbit and hence observed TOAs properly. A list of the known double neutron star binaries is

¹) <http://pulsar.princeton.edu/tempo/index.html>

²) Although most non-degenerate stars are in binary systems, most pulsars are isolated because supernova explosions usually disrupt binaries. See Bhattacharya & van den Heuvel (1991) for a review of the circumstances under which binary pulsars form.

Table 1: Double Neutron Star Binaries^{a,b,c}

PSR	P_b	e	measured PK parameter	Reference
J1518+4904	8.6 day	0.25	$\dot{\omega}$	Nice, Sayer & Taylor (1996)
B1534+12	10.1 hr	0.27	$\dot{\omega}, \gamma, \dot{P}_b, r, s$	see text
J1811–1736	18.8 day	0.83	$\dot{\omega}$	Lyne et al. (1999)
B1913+16	7.8 hr	0.62	$\dot{\omega}, \gamma, \dot{P}_b$	see text
B2127+11C	8.0 hr	0.68	$\dot{\omega}$	Prince et al. (1991)

^aSources suitable for tests of GR are indicated in bold.

^bPSR B1820–11 is not included as the nature of its companion is uncertain [Phinney & Verbunt 1991].

^cPSR B2303+46, previously thought to have a neutron-star companion, has recently been shown to have a white dwarf companion [van Kerkwijk & Kulkarni 1999].

given in Table 1. The only non-classical post-Keplerian (PK) effects to have been measured in a binary pulsar system thus far are: the rate of periastron advance $\dot{\omega}$, the combined effects of relativistic Doppler shift and time dilation γ (equivalent to the solar system Einstein delay – see Eq. 1), the rate of orbital decay \dot{P}_b , and r and s , the two parameters describing the Shapiro Delay, or the observed pulse time delay due to the bending of space-time near the pulsar companion, important for highly inclined orbits (equivalent to Δt_s in Eq. 1). The relativistic post-Keplerian parameters measured in each of the known double neutron star binaries are given in Table 1. The systems for which tests of theories of relativistic gravity are possible are indicated by bold type: these are binaries for which N post-Keplerian parameters are measurable, where $N > 2$. These systems permit $N - 2$ tests of gravity, as the first two parameters determine the masses of the two components.

Overall, the suitability of a binary pulsar system for tests of GR or other theories of gravity is determined by a number of factors, including orbital period, orbital eccentricity, orbital inclination angle, the morphology of the pulse profile (narrower pulses permit higher measurement precision) and of course, the pulsar’s radio flux. For example, PSR B2127+11C, though in a binary system that is superb for testing GR [Prince et al. 1991], is faint (it was discovered in a deep search of the globular cluster M15) and has thus far not permitted any tests of GR.

PSR B1913+16

The results of long-term timing observations of the relativistic binary pulsar PSR B1913+16 are well-known; indeed they have been distinguished with the 1993 Nobel Prize in Physics awarded to the discoverers Joseph Taylor and Russell Hulse. Detailed descriptions and reviews of the results and implications of those timing observations can be found in a variety of references [Hulse & Taylor 1975, Taylor et al. 1976, Taylor & Weisberg 1982, Taylor 1987, Taylor & Weisberg 1989, Damour & Taylor 1991, Taylor et al. 1992, Damour & Taylor 1992, Taylor 1992, Taylor 1993]. Here we briefly summarize the status of those observations, and discuss the recently reported evidence for geodetic precession in this system.

Status of Timing Observations of PSR B1913+16

As reported by Taylor (1993), timing observations of the 59 ms PSR B1913+16 made at the 305 m radio telescope at Arecibo, Puerto Rico through 1993 (the Arecibo telescope became inoperable not long afterward in preparation for a major upgrade, which is nearly complete) have resulted in the determination of three post-Keplerian parameters: the rate of periastron advance $\dot{\omega} = 4^\circ.226621 \pm 0^\circ.000011$, the combined time dilation and gravitational redshift $\gamma = 4.295 \pm 0.002$ ms, and the observed orbital period derivative $\dot{P}_b = (-2.4225 \pm 0.0066) \times 10^{-12}$. The first two of these parameters determine the component masses to be $1.4411 \pm 0.0007 M_\odot$ and $1.3874 \pm 0.0007 M_\odot$. The third post-Keplerian parameter, \dot{P}_b , in principle allows for one test of GR (or other theory of gravity).

However, the observed value of \dot{P}_b must first be corrected for the effect of acceleration in the Galactic potential. This correction follows from the simple first-order Doppler effect, where $P_b^{obs}/P_b^{int} = 1 + v_R/c$, where P_b^{obs} and P_b^{int} are the observed and intrinsic values, and v_R is the radial velocity of the pulsar relative to the solar system barycentre. A changing v_R leads to a Galactic term

$$\left(\frac{\dot{P}_b}{P_b}\right) = \frac{a_R}{c} + \frac{v_T^2}{cd}, \quad (2)$$

where a_R is the radial component of the acceleration, v_T is the transverse velocity, and d is the distance to the pulsar. The second term in this equation is the familiar transverse Doppler or “train-whistle” effect. The best estimate correction factor for PSR B1913+16, given its only approximately known location in the Galaxy, is $(-0.0124 \pm 0.0064) \times 10^{-12}$ [Damour & Taylor 1991, Taylor 1992]. With this correction applied to \dot{P}_b^{obs} , the comparison with the GR prediction can be made; the result [Taylor 1992] is that

$$\frac{\dot{P}_b^{obs}}{\dot{P}_b^{GR}} = 1.0032 \pm 0.0035. \quad (3)$$

Note that the uncertainty in this expression is dominated by the uncertainty in the Galactic acceleration term. Since a_R and d are unlikely to be known with much greater precision than is currently available, this particular test of GR will probably not improve much in the near future.

Additional tests of GR may still be possible with the PSR B1913+16 system if the parameters r and s can be measured. This may be possible given the recent major upgrade to the Arecibo telescope, as higher timing precision should now be available.

PSR B1913+16 and Geodetic Precession

Relativistic geodetic precession, the gravitational analogue of Thomas precession (the origin of fine structure in atomic spectra), is predicted to result in a changing

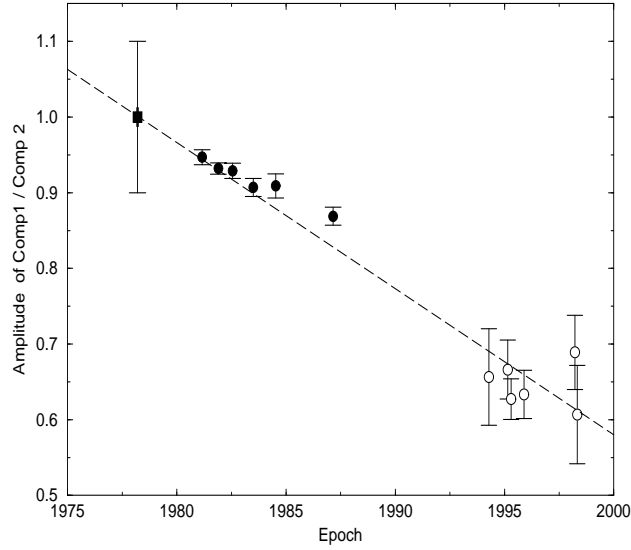


FIGURE 2. The variation in the ratio of the amplitudes of the components of the PSR B1913+16 average radio pulse profile, after Kramer (1998).

orientation of the pulsar spin axis. As the pulsar precesses, our line of sight should intersect different parts of the radio emission beam. Thus, the average pulse profile could vary significantly over time. The first evidence for this in the PSR B1913+16 system was presented by Weisberg, Romani & Taylor (1989) [but see also Cordes, Wasserman & Blaskiewicz 1990]. They reported a gradual, secular evolution in the ratio of the amplitudes of the two pulse peaks (see Fig. 1).

Recently, Kramer (1998) has clearly demonstrated that this trend continues. Figure 2 shows the ratio of the amplitudes of the two pulse components as a function of time; the variation is striking. If the emission results from a cone of radiation, then a secular change in the separation of the two peaks ought to be observed as well; strong evidence for this is also now seen [Kramer 1998]. Quantitative modeling of this variation depends on the unknown beam morphology. Under the assumption of a hollow, circular emission beam, if GR is correct, Kramer shows that the pulsar, sadly, will no longer grace the skies of our Earth after the year 2025. Happily however, it should reappear around the year 2220. The exact dates of disappearance, together with the form of the secular variation in average pulse morphology, will permit the first direct observation and study of the morphology of a radio pulsar emission beam.

PSR B1534+12

The binary pulsar PSR B1534+12 was discovered by Wolszczan (1991) using the Arecibo telescope. This 38 ms pulsar is in a 10 hr eccentric orbit with a second neutron star (see Table 1). PSR B1534+12 offers the hope of additional and more precise tests of GR for a number of reasons: first, the narrower pulse profile of PSR B1534+12 (Fig. 1) means higher timing precision. Second, the orbital plane of this system is more inclined than that of PSR B1913+16, which facilitates the measurements of two additional relativistic parameters r and s . Thus, in principle, five relativistic post-Keplerian parameters are measurable with high precision for PSR B1534+12, which allows two new additional tests of GR that have not been done for PSR B1913+16. This is particularly important for testing alternative theories of gravity, as it permits the separation of the radiative and strong-field components of the theory. This cannot be accomplished in the simple $\dot{\omega}$ - γ - \dot{P}_b test, as it mixes radiative and non-radiative effects [see Damour & Taylor 1992 for details].

Stairs et al. (1998) report on seven years of timing observations of PSR B1534+12 made at Arecibo, at the 43 m dish at Green Bank, as well as at the 76 m Lovell radio telescope at Jodrell Bank. As expected, they measure the five post-Keplerian relativistic parameters $\dot{\omega}$, γ , \dot{P}_b , r and s . The results are nicely summarized in Figure 3 (Fig. 4 in Stairs et al. 1998), where the component masses are plotted on the axes. As each of the five post-Keplerian parameters has a different dependence on the masses, each parameter defines a curve in this plane. If GR holds, then the five curves, as calculated in GR, should meet at a single point. As can be seen in Figure 3, the curves for $\dot{\omega}$, γ and s agree to better than 1% (though that for r is not yet precise enough to be very constraining). Surprisingly, their intersection implies that the pulsar and companion have exactly equal masses within uncertainties, $1.339 \pm 0.003 M_\odot$.

As is clear in Figure 3, the curve for \dot{P}_b just misses this intersection point. Note, however, that the value of \dot{P}_b used to produce the curve in Figure 3 included a correction for Galactic acceleration (Eq. 2) that assumed a distance of 0.7 kpc to the pulsar, from its observed DM and the best model for the free electron distribution [Taylor & Cordes 1993]. The model is known to be only approximate, with uncertainties on inferred distance for anyone source optimistically 25%, and realistically considerably larger. Stairs et al. therefore argue that the discrepancy seen in Figure 3 can be removed by simply invoking a larger distance to the pulsar, 1.1 kpc. Put differently, by assuming GR is correct, the distance to this relativistic binary pulsar can be determined with greater precision than is otherwise available [Bell & Bailes 1996]. This demonstrates that the measurement of an improved \dot{P}_b for PSR B1534+12 is unlikely to offer a useful test of GR unless the distance to the source can be determined independently (for example, via a timing or interferometric parallax measurement). However, the expected improved determination of the r parameter, following the Arecibo upgrade, could yield a useful test in addition to that from $\dot{\omega}$ - γ - s .

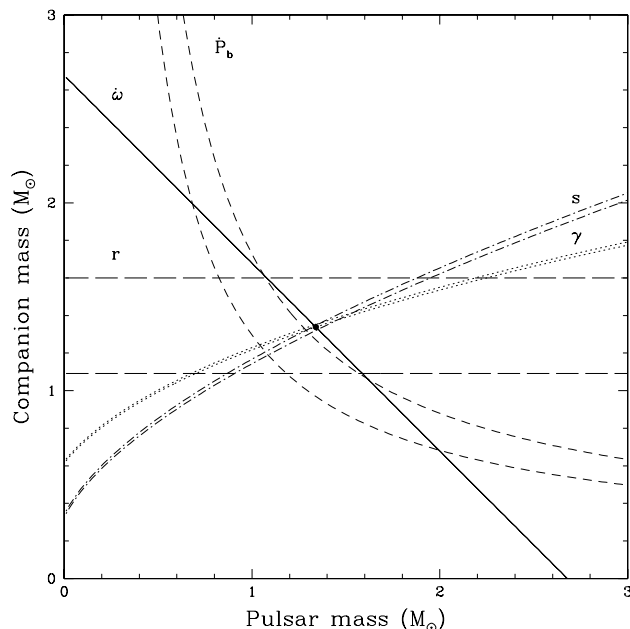


FIGURE 3. The constraints imposed by the observed values of the five measured post-Keplerian parameters on the masses of the components of PSR B1534+12, after Stairs et al. (1998).

The improved distance determination to PSR B1534+12 made by Stairs et al. (1998) has implications for estimates of the coalescence rate of double neutron star binaries. A larger distance implies a more intrinsically luminous pulsar, which in turn implies that there are fewer in the Galaxy, as otherwise more would be detected. Stairs et al. suggest that the expected rate must be reduced relative to previous estimates [Phinney 1991, Curran & Lorimer 1995, van den Heuvel & Lorimer 1996] by factors of 2.5–20. This rate is of considerable interest to the builders of gravitational wave detectors like LIGO (see paper by P. Saulson, this volume). Of course rates that vary greatly depending on the estimated distance to a single object should be regarded as crude estimates only.

FINDING MORE RELATIVISTIC BINARIES: THE PARKES MULTIBEAM SURVEY

A major survey of the Galactic Plane for radio pulsars is currently underway. This survey offers the hope of finding new examples of relativistic binary pulsars suitable for studying GR effects. The observations are being done using the Parkes 64 m radio telescope in Australia [Lyne et al. 1999]. The survey is planned to cover the inner Galactic Plane, in the Galactic longitude range $260^\circ < l < 50^\circ$ and Galactic latitude range $|b| < 5^\circ$. The search is being carried out at radio frequencies near 1400 MHz and has roughly seven times the sensitivity of previous

1400 MHz surveys of the Galactic Plane [Clifton & Lyne 1986, Johnston et al. 1992], owing mainly to the longer integration time permitted by the use of the new multibeam receiver at Parkes. This new instrument consists of 13 independent, non-overlapping receivers in the telescope focal plane. This allows the Galaxy to be surveyed to much greater depth than was previously possible, without using a prohibitive amount of telescope time. Each beam pointing consists of a 35 min integration, with a total of 288 MHz bandwidth 1-bit sampled every 250 μ s. Some 35,000 beams will be observed, and the data for each will be subject to a Fast Fourier Transform of 2^{23} points. The project is thus computer resource intensive. With approximately half of the survey complete, 405 previously unknown radio pulsars have been discovered, making this by far the most successful pulsar survey ever.

Among the first sources found in the survey is the very likely double neutron star binary PSR J1811–1736 (see Table 1) [Lyne et al. 1999]. Although this system is unlikely to be useful for tests of GR, its early discovery in the survey suggests there are many more such systems to be found. Indeed, not long after the conference for which these proceedings are a record, a third relativistic binary pulsar suitable for tests of GR was discovered among the new Parkes Multibeam sources. Detailed observations of this exciting source are just getting underway as this paper is being written.

CONCLUSIONS

The now famous technique of timing relativistic binary pulsars has yielded confirmation that GR is the correct theory of gravity at better than the 1% level. Future additional tests of GR, using the only two known sources well-suited to such tests, PSR B1534+12 and PSR B1913+16, are possible, from improved measurements of the Shapiro delay r and s parameters. The precision in the $\dot{\omega}$ - γ - \dot{P}_b test is limited by the uncertainty in our estimates for the Galactic acceleration of these objects. However, under the now justified assumption that GR is correct, observations of relativistic binary pulsars can yield unique astrophysical measurements that have never before been possible, including precise determination of neutron star masses, distances to these sources, LIGO source rates, and morphological studies of the pulsar radio emission beam. The ongoing Parkes Multibeam survey of the Galactic Plane promises (and indeed has already begun) to discover new examples of these fascinating objects.

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